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AD-A263 132

NRL/MR/4793--93-7197

Study of Gain in C-Band Deflection Cavities for a Frequency-Doubling Magnicon Amplifier

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March 26, 1993

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave Blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 26, 1993	Interum

4. TITLE AND SUBTITLE

Study of Gain in C-Band Deflection Cavities for a Frequency-Doubling Magnicon Amplifier

5. FUNDING NUMBERS

67-3046-03
67-3788-03

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) and ADDRESS(ES)

Naval Research Laboratory
Washington, DC 20375-5320

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/6793--93-7197

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Chief of Naval Research, Arlington, VA 22217
U.S. Department of Energy, Washington, DC 20545

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

*Icarus Research, 7113 Exfair Road, Bethesda, MD 20814

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (*Maximum 200 words*)

We report an experimental study of the gain between two half-wavelength, 5.7 GHz TM_{110} pillbox cavities, separated by a quarter-wavelength drift space, and powered by a 170A, 500 keV electron beam immersed in an 8.1 kG magnetic field. These cavities constitute the first section of a planned multicavity deflection system, whose purpose is to spin up an electron beam to high transverse momentum for injection into the output cavity of a frequency-doubling magnicon amplifier. We have observed a gain of ~15 dB in the preferred circular polarization, at a frequency shift of approximately -0.18%, and a gain of ~3 dB in the opposite circular polarization, at a frequency shift of approximately +0.06%. These results are in good agreement with theory.

14. SUBJECT TERMS		15. NUMBER OF PAGES
Magnicon	C-Band	22
Gyrocon		16. PRICE CODE
Amplifier		

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

CONTENTS

STUDY OF GAIN IN C-BAND DEFLECTION CAVITIES FOR A FREQUENCY-DOUBLING MAGNICON AMPLIFIER

I. Introduction

The magnicon,[1-3] a "scanning beam" microwave amplifier tube related to the gyrocon,[4] is of interest as a possible replacement for klystron amplifiers in future linear accelerators. It offers the potential of higher power operation at frequencies above 10 GHz, higher efficiency, and reduced sensitivity to variations in the load, while maintaining the traditional klystron advantage of high gain and frequency and phase stability. It consists of a number of TM-mode deflection cavities (a drive cavity and a series of gain cavities), separated by drift spaces, that are designed to spin up an electron beam to high transverse momentum ($\alpha \equiv v_\perp/v_z \gtrsim 1$, where $v_\perp$ and v_z are the velocity components perpendicular and parallel to the axial magnetic field), followed by a gyrotron-like TM-mode output cavity that is designed to extract principally the transverse electron momentum in a gyroresonant interaction. The deflection cavities employ a rotating TM_{110} mode, producing a gyrating electron beam whose instantaneous position and guiding center, at the entrance to the output cavity, both rotate about the cavity axis at the drive frequency. The output cavity operates near cyclotron resonance and employs a mode that rotates synchronously with the guiding center of the electron beam (a TM_{210} mode in the case of a frequency doubling magnicon amplifier). By this means, complete phase bunching is achieved, making possible a highly efficient output interaction.

In this paper, we report a measurement of the gain between two deflection cavities, the first driven and the second passive. These measurements were carried out to test the agreement between theory and experiment, in preparation for the design of a complete deflection system that will spin up an electron beam to high transverse momentum for injection into an 11.4 GHz output cavity.

Manuscript approved February 5, 1993.

II. Apparatus

This experiment was carried out on the NRL Long-Pulse Accelerator Facility.[5] It employed a field-emission diode [see Fig. 1], designed with a flat magnetic field of 1.7 kG in the anode-cathode gap, followed by adiabatic compression to a final magnetic field of 8.1 kG, to generate a 500 keV, ~200 A, 5.5 mm diam solid electron beam with low initial transverse momentum. Simulation results using a version of the Stanford Electron Optics Code[6] suggest a mean $\alpha \sim 0.03$. This beam was used to power a two-cavity amplifier experiment. The two cavities are of identical pillbox design. They were fabricated from stainless steel, to permit the penetration of pulsed magnetic fields, with a copper coating on the interior surfaces to decrease the ohmic losses. Each has four coupling pins spaced at 90° intervals in one end-wall. Two adjacent "coupling" pins are "long," for use in driving the two linear polarizations of the cavity, and the remaining two "sampling" pins are "short," in order to measure the cavity fields without significantly loading the cavity. The pins lead to coaxial signal cables through type "N" connectors. The first cavity was driven in a circularly-polarized TM_{110} mode by a C-band magnetron at ~5.7 GHz. Circular polarization was generated by driving the two coupling pins with a $\pi/2$ phase difference using a 3 dB hybrid coupler. In the second (gain) cavity, the two sampling pins lead to matched loads, while the two coupling pins were connected through coaxial attenuators to crystal detectors.

The cavities, their pickups, and all other microwave components were fully calibrated using a microwave scalar network analyzer. The energy/power relationship for each cavity is given by the usual formula, $P=\omega W/Q$, where P is the power loss, ω is the angular frequency of the radiation, W is the energy stored in the cavity, and Q is the cavity quality factor. When there are several loss terms (e.g., ohmic loss, coupling loss, sampling loss, beam loading), each may be associated with a separate power P_i and quality factor Q_i, as $P_i = \omega W/Q_i$, where the total power loss is $P_{tot} = \sum_i P_i$ and the

total cavity quality factor is determined by $Q_{tot}^{-1} = \sum_i Q_i^{-1}$. One may also define an internal quality factor, Q_{int}, as the total Q (with or without beam loading), not including the losses associated with the coupling pins. Q_{int} determines the cavity losses seen when the cavity is externally driven, and can also be used to calculated the cavity reflection coefficient. Cold tests of each cavity were used to establish the center frequency, and the sampling, coupling, and total Q values in each linear polarization in the absence of the electron beam [see Table I]. Note that the coupling Q's dominate the overall cavity Q factors. With the overall cavity characteristics strongly dependent on the output coupling, great care must be taken in the matching of each coaxial transmission line connected to a coupling pin. In order to preserve the matching conditions for the gain cavity, high power 20 dB attenuators were connected by short lengths of high quality coaxial cable to the coupling pins during both the cold tests and the actual experimental measurements. Using the values in Table I, the response function of the drive cavity in the presence of the electron beam, and the gain of the second cavity can be determined experimentally. In order to compare with the predictions of theory, gain (dB) is defined as 10 log (W_2/W_1), where W_j is the energy stored in the j^{th} cavity (rather than being defined in terms of the drive power and the amplified signal, as it would be for a practical amplifier).

Five microwave signals were monitored on each experimental discharge, including the magnetron signal, signals from each linearly polarized sampling pin of the first cavity, and signals from each coupling pin of the second cavity. In addition, a balanced mixer was used to combine the first cavity signal with the signal from a separate local oscillator tuned as closely as possible to the operating frequency of the magnetron. This "mixed" signal was used to set the exact magnetron frequency (using a mechanical tuner), to adjust the magnetron voltage to avoid excessive frequency chirp, and to guard against frequency drift. In addition, phase or frequency shifts due to the effects of the beam on the drive cavity could be observed.

The axial electric field of the TM_{110} mode, in combination with the strong axial magnetic field required for the electron–wave interaction, creates conditions favorable for multipactor breakdown in the deflection cavities. The experimental multipactor threshold can be influenced by many things, including cavity surface finish, local electric field enhancements (such as at the coupling pins), surface cleanliness, and background vacuum pressure. The threshold for multipactor in the drive cavity, in the presence of the axial magnetic field, was observed to occur at levels of drive power ranging from a few kW to 50 kW in different experimental runs. This variation may correspond in part to different degrees of surface cleanliness. In order to make an unambiguous test of the linear interaction theory, the experimental gain measurements were carried out with drive powers of 10–400 W, well below the point that any evidence of multipactor occurred in the gain cavity.

III. Magnicon theory and simulation

The linear theory of the magnetized deflection cavities was first presented by Karliner, *et al.*[1] It was extended to include the effect of finite beam emittance by Hafizi, *et al.*[7] The analyses assume that the electron energy and axial velocity are constants as the beam is spun up in the deflection cavities. In the linear approximation, the solution of the wave equation leads to the usual Lorentzian profile for the response function of the first cavity and for the gain curve of the second cavity. The gyration of the electrons in the guide field breaks the symmetry of the system, and therefore the response of the two cavities is different for the two circular polarizations. Only the "preferred" circular polarization, which corresponds to electron gyromotion in the same sense as the rotation of the mode, leads to high intercavity gain. (The results of Ref. [7] may be applied to the "opposite" circular polarization by making the substitution $\omega \to -\omega$ in the appropriate formulae.) For the input cavity, the effect of the electron beam is manifested by a modification to the Q and the center frequency

of the response function from the nominal values. For the particular case of the preferred circular polarization, and for $\omega_c=2\omega$, where ω_c is the relativistic electron gyrofrequency, the electrons are deflected in the first cavity without gaining or losing energy, and the beam has no effect on the overall cavity Q.

A numerical simulation code for the deflection cavities has also been developed.[7] It is a self-consistent steady-state code that integrates the full Lorentz equations for a finite-emittance beam of electrons through the TM_{110} fields of the first (driven) deflection cavity, through the drift space, and then through successive passive cavities whose field amplitudes are iteratively adjusted to be in power balance with the loss of electron beam energy. The rf phase in each passive cavity is assumed to be the optimum phase to extract energy from an initially on-axis electron, since this should be a good approximation to the phase that will be driven by a real electron beam.

Comparison of the simulation results with the linear analysis indicates that the assumption of constant electron energy and axial velocity is a good approximation in all but the final cavity of a complete ($\alpha_{final} \geq 1$) deflection system. Additionally, for the initial velocity spread predicted for the electron beam, the reduction in the gain of a two-cavity system is relatively small. In what follows, we shall therefore compare the experimental results with those from the linear theory of an ideal electron beam.

IV. Experimental Results

The response of the first cavity, and the gain of the second cavity, as a function of frequency, were measured in each circular polarization of the TM_{110} mode. The measurements were carried out at 500 keV, with a beam current of ~170 A, and a magnetic field of 8.1 kG. For these measurements, the accelerator voltage was adjusted so that the droop (~12%/μs) passed through 500 kV approximately 300 ns into a 500 ns pulse. Microwave measurements were recorded corresponding to the

average over a ±100 nsec window centered about this point. By this means, transient effects associated with the voltage rise and fall could be discriminated against. The magnetic field corresponds to the theoretical value at which, for the preferred circular polarization, the beam does not load the cavity Q.

The predicted and measured response of the first cavity as a function of frequency in each circular polarization are shown in Figs. 2 and 3. Simultaneous measurements are made at the cavity sampling pins in each linear polarization of the cavity, with the coupling pins driven at equal signal levels with a $\pm\pi/2$ phase difference by a hybrid coupler. The linearly polarized measurements were kept separate, so that the statistical error bars would not be influenced by systematic errors in the relative calibrations of the separate signals. The data are normalized to the calculated signal level from the cavity at constant magnetron drive power at the center of the cold cavity resonance in the absence of the electron beam. This normalization is based on cold tests of all components of the system.

Figure 2 shows the theory and data for the preferred circular polarization, in which the mode co-rotates with the electron gyromotion. Theory predicts that the center of the resonance will be shifted by –0.18%, and that the beam loading should be very close to zero. This is indicated by a curve whose height is normalized to one, and whose width is consistent with Q_{tot} ~1100 [see Table I]. The experimental data are in good agreement with theory, with respect to both the width and the center frequency of the drive cavity response function. In addition, while the experimental data for the two linear polarizations consistently differ by ~3 dB, perhaps due to cumulative calibration errors, the two separate data sets bracket the theoretical response curve.

Figure 3 shows the theory and data for the opposite circular polarization. In this case, theory predicts a frequency shift that is positive and one third as large (+0.06%). Theory also predicts that the cavity quality factor associated with beam loading is Q_{beam}=965. This causes a factor of five reduction in Q_{int}, reducing the

amplitude of the cavity response curve to 0.22, and a factor of two reduction in Q_{tot}, doubling the width of the response curve. In this case also, the width and center frequency of the data are in good agreement with theory, while the height differs by ~1 dB.

The splitting of the two circular polarizations in the presence of the beam indicates that it is not necessary to drive both linear polarizations, with an appropriate phase shift, in order to generate the correct circular polarization: at the hot cavity resonant frequency, the only mode available has the correct circular polarization. Experimentally, driving just one coupling pin of the drive cavity, in the presence of the beam, produces approximately equal coupling to each linearly polarized sampling pin.

The predicted and measured gain of the second cavity in each circular polarization are shown in Figs. 4 and 5. For the preferred circular polarization (see Fig. 4), theory predicts a gain of ~15 dB, with the resonance shifted by -0.18% from the cold frequency of the second cavity. The experimental gain measurements are in good agreement with the theoretical curve in amplitude, center frequency, and bandwidth. However, there is a persistent imbalance in the two linear polarizations, which may be in part calibration error, but also may reflect a true asymmetry in the cavity excitation (elliptical polarization), perhaps due to a small misalignment of the electron beam, or some asymmetry in the mode of the drive cavity. For the opposite circular polarization (see Fig. 5), theory predicts a substantially lower gain (~2 dB), combined with a frequency shift of +0.06%. The experimental data for this circular polarization are also in general agreement with theory. However, there is more scatter in the data points, and the experimental gain appears to be a few dB higher than the theoretical curve.

V. Discussion

The overall purpose of a complete set of magnicon deflection cavities is to coherently spin up an electron beam to high α for injection into an output cavity. With this overall goal in mind, the present experiment was designed to measure the gain between a driven and a passive deflection cavity, which could constitute the first section of a complete deflection system. In this two–cavity experiment, high gain (~15 dB) was observed in the preferred circular polarization, in good agreement with the predictions of theory. However, one should note that the present experiment was carried out at very low signal levels, in order to eliminate the possibility of multipactor phenomena interfering with the basic gain measurement. Under these conditions, the resulting coherent beam α should be quite small ($\lesssim 0.01$). This is less than the initial random α produced by the diode. In future experiments, higher drive powers and additional deflection cavities will be employed, in order to achieve a final $\alpha \gtrsim 1$. An important requirement in those experiments will be the suppression of multipactor and breakdown effects through a combination of improved cavity design and improved vacuum techniques. The effect of initial electron radial and velocity spreads on the gain measured in the present experiment is predicted to be quite small. Nevertheless, such spreads may have a large effect on the quality of the final high α electron beam generated by a full sequence of deflection cavities, resulting in a lowering of the efficiency of the output cavity interaction.[8] In this regard, the real test of the final multicavity deflection system will be to produce a high α electron beam, while minimizing the spread in energy, α , and gyrophase.

Acknowledgments

This work was supported by the U.S. Department of Energy under Interagency Agreement No. DE–AI05–91ER40638. It was also supported in part by the Office of Naval Research. We acknowledge useful discussions with R. Gilgenbach, J. Choi,

A. Fisher, and E. Garate on aspects of our diode design, and with O. Nezhevenko on some aspects of magnicon physics. We are also grateful to W. M. Black for his assistance in the design of our diode magnetic field coils.

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TABLE I

PROPERTIES OF TM_{110} DEFLECTION CAVITIES

Cavity #	Polarization	f_0 (GHz)*	Q_{tot}	Q_{couple}	Q_{sample}
1	1	5.682	1110	1630	90400
1	2	5.683	1100	1690	96200
2	1	5.680	970	1400	**
2	2	5 .6805	950	1300	**

*Values in vacuo.

**Value not determined.

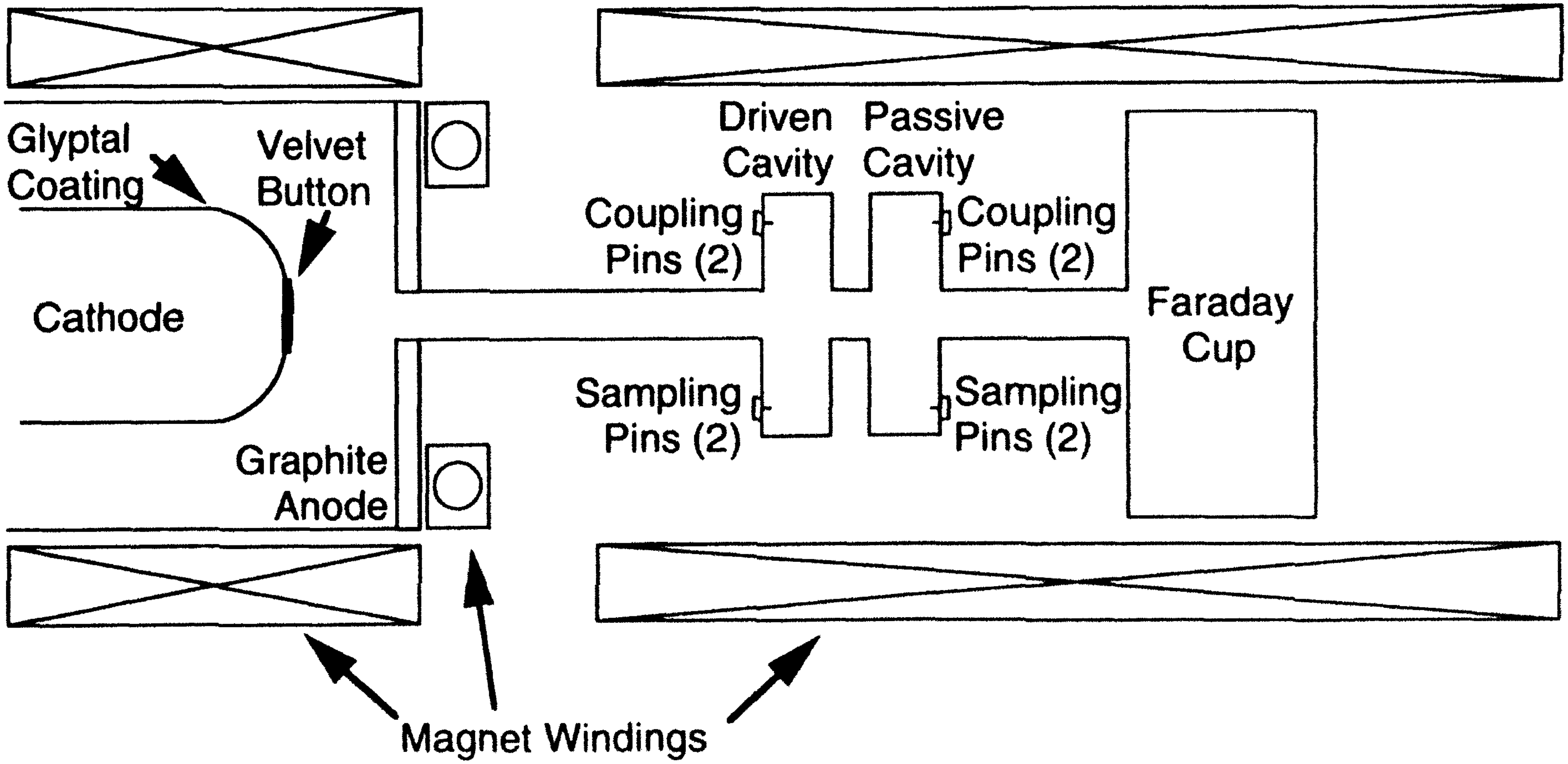

Figure 1. Schematic of the two-cavity gain experiment

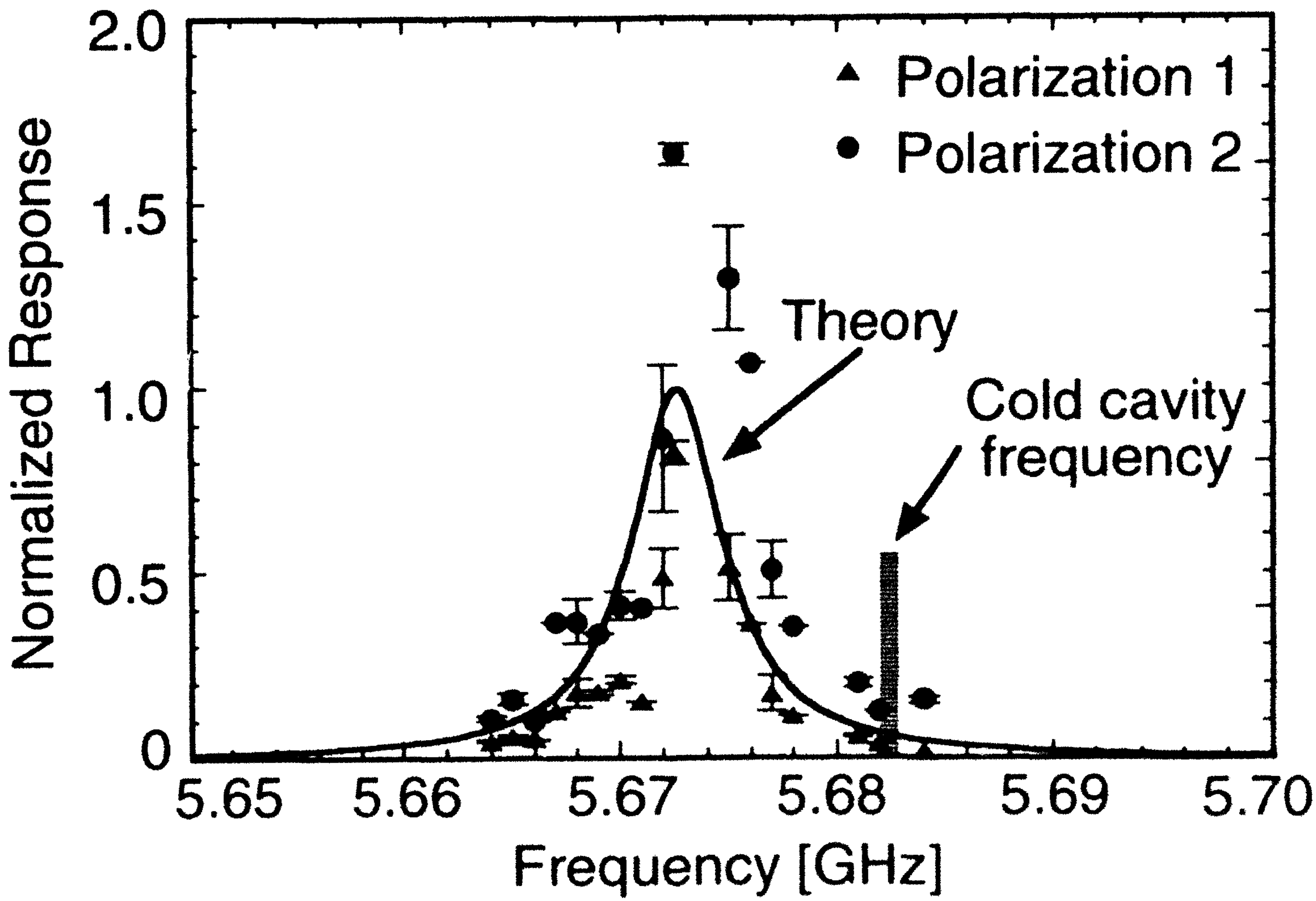

Figure 2. Response of the drive cavity in the preferred circular polarization as a function of frequency, normalized to the magnetron drive signal. The cold cavity resonant frequency, the theoretical response curve, and the measurements in the two linear polarizations of the drive cavity are shown.

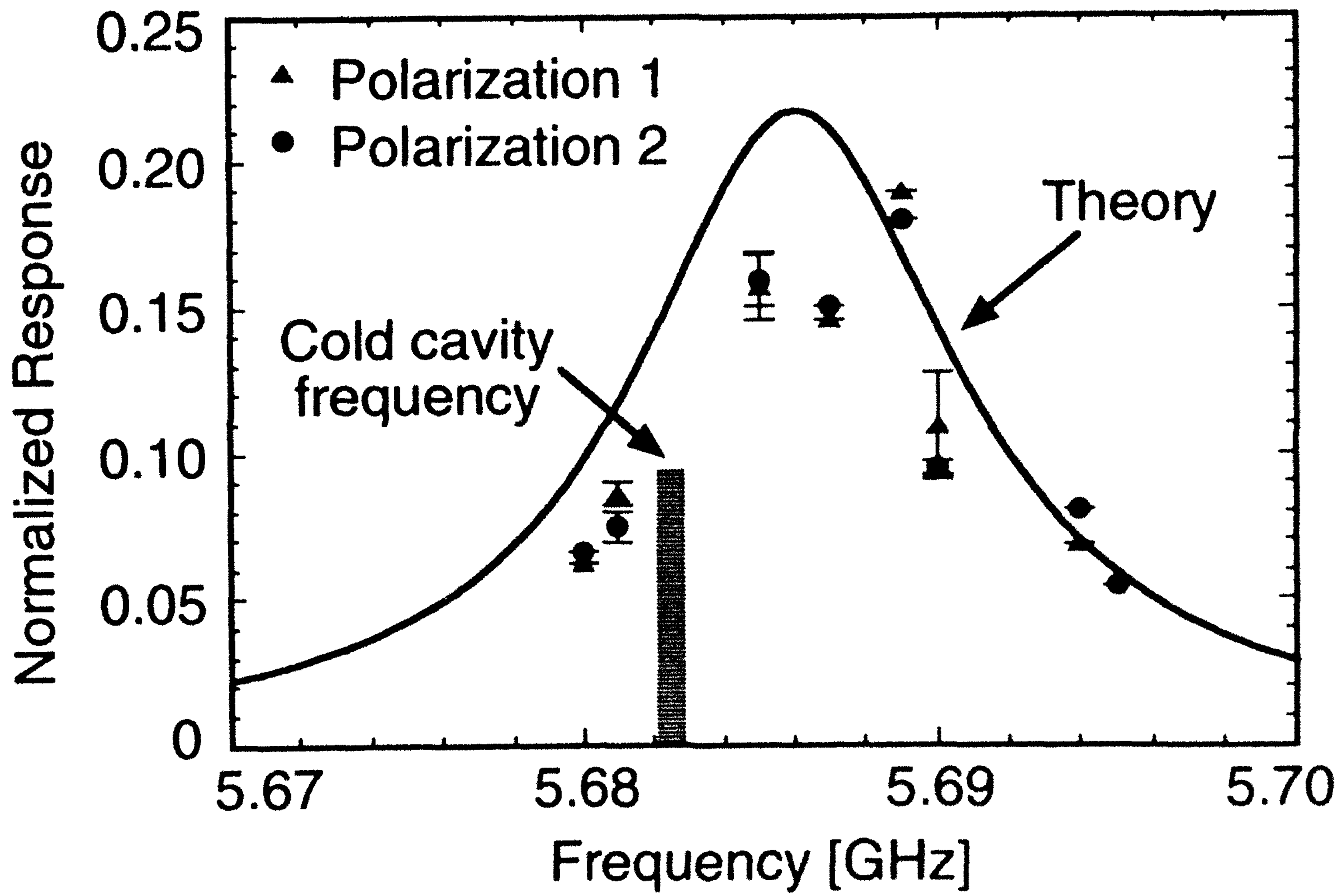

Figure 3. Response of the drive cavity in the opposite circular polarization.

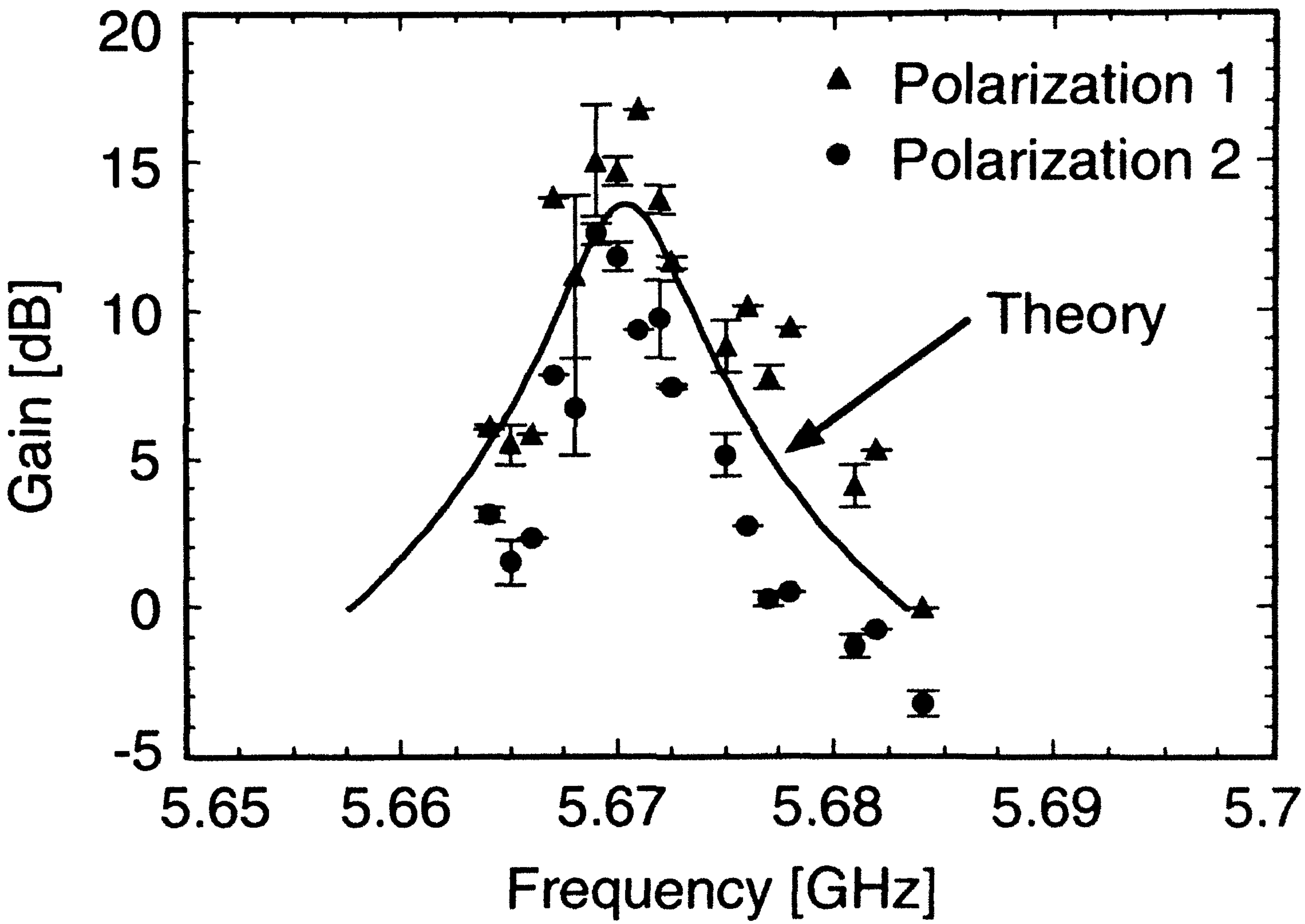

Figure 4. Gain of the second cavity as a function of frequency, with the drive cavity excited in the preferred circular polarization. The theoretical gain curve, and the measurements in the two linear polarizations of the gain cavity are shown.

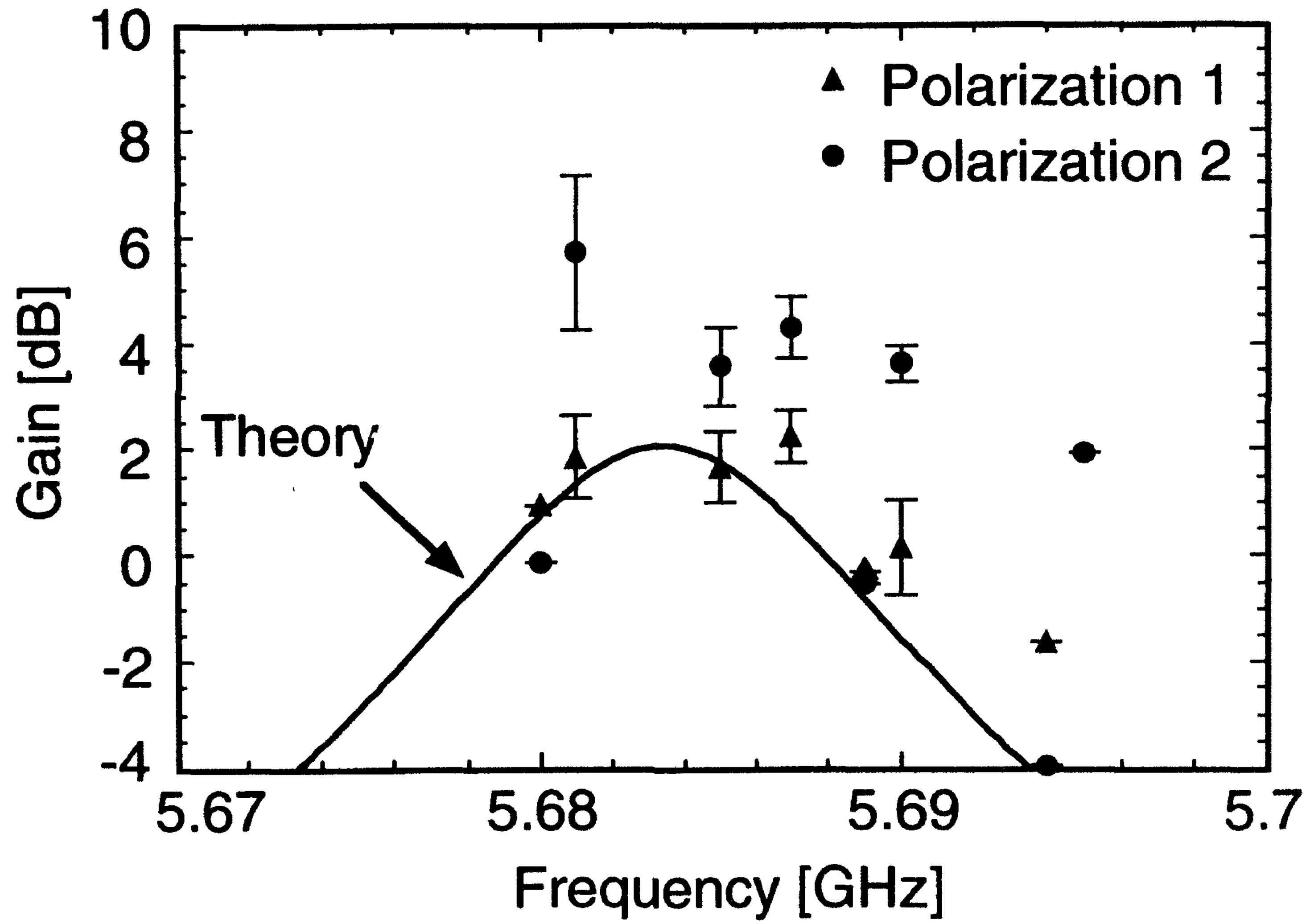

Figure 5. Gain of the second cavity as a function of frequency, with the drive cavity excited in the opposite circular polarization.